ABSTRACT

Phase One of the Niger Delta Pressure Study (Deep and Ultra-Deep Water) has expanded our knowledge of subsurface pressure through the analysis of more than 90% of the available deep water and ultra-deep water wells in the region. Many of the wells encountered overpressures (pressure above normal) which is expected given their depth age and depositional setting. However, the magnitude of overpressure is lower than expected, given the rate of sedimentation of this active delta. The pressure study has created a database from which it has been possible to develop a methodology for prediction of pore pressure, overburden and fracture pressure anywhere within the study area. Wireline logs from more than 150 wells were analysed for shale pressures, and compared to direct measurement of reservoir pressures where available. The comparison leads to conclusions about regional reservoir connectivity, vertical pressure communication and seal effectiveness. Both regional and local relationships to describe fracture pressure and overburden have been developed, all of which lead to more confidence for subsurface prediction in future drilling targets. In addition, the nature of regional reservoir connectivity predicts trapping geometries and relationships between hydrocarbons and fluid flow phenomena which would otherwise be ignored. Careful analysis of pressure data in producing fields confirms many of these relationships.

Introduction

The benefits of regional pressure analysis is best described in terms of improved safety based on better calibrated and hence more accurate pressure predictions, as well as identification of new reserves/exploration opportunities related to improved understanding of seals and reservoir leakage. Ikon GeoPressure have been conducting region-wide pressure studies since 2003 and have developed workflows which integrate all the relevant data to establish pore pressure and fracture gradient prediction criteria as well as detailed description of the distribution of overpressure and hence reservoir connectivity/compartmentalisation. Operators of licence blocks can then take the “Regional” to inform the “Local” and thereby understand the significance of data from only a small number of offset wells around a drillable prospect. Following the BP Macondo drilling and spill incident in 2010 there has been increased attention paid to pressure prediction, in particular in Deep Water settings. The completion of the Niger Delta Pressure Study Phase One (Deep Water and Ultra-Deep Water) in early 2011 is therefore extremely timely for the Nigerian Oil and Gas industry, providing the basis for detailed pressure analysis in advance of renewed activity in Deep Water/ Ultra-Deep Water licence blocks. Further phases of the study are following to cover the Continental Shelf (Phase Two) and the Onshore/Swamp (Phase Three) where the challenges related to pressure are especially great beyond current drilling depths.

Improved Safety and Cost Saving

Drilling, especially in high pressure areas such as Tertiary Deltas (of which the Niger Delta is a world-class example), requires a well plan involving both pore pressure and fracture gradient prediction. Pore pressures are largely determined by analysis of relevant data coupled with knowledge of burial, stress and temperature histories, rock types and their distributions and subsurface structure and reservoir connectivity. Fracture gradients are largely controlled by rock properties where lithology, compaction...
state, degree of lithification, within a context of the regional and local stresses. Prediction of both pore pressure and fracture gradient away from local well control can be very challenging, and it is not uncommon to find unscheduled downtime resulting from actual pressures which vary from the predictions. Hence any approach which can reduce unscheduled downtime is saving well costs, and more accurate predictions will also reduce the likelihood of influxes and mud losses which improve safety of the well operations.

**Pore Pressure Prediction**

Pore pressure prediction is typically based on analysis of shale compaction, as imaged using seismic, log and/or drilling data trends where changes in the data relate to compaction and porosity of the shales. The workflow involves analysis of porosity trends to establish a “normal compaction trend” (NCT) from which the magnitude of pressure and overpressure can be established using industry-standard algorithms (Figure 1). A normal compaction trend has to be established for each data type. The DPR/NDR were able to provide data from over 90% of the drilling locations in the Deep Water/Ultra-Deep Water Niger Delta area. Regional and sub-regional NCTs were established as part of the study using Sonic, Resistivity and Density data and results compared across the delta. Whilst there were differences from one area to another, there was a remarkable consistency of trends, resulting in recommended regional NCTs which can be used with confidence for use in pore pressure prediction.

To solve for pore pressure also required knowledge of the overburden stress (also termed vertical stress). A regional overburden model was established and applied to over 150 wells in the Deep Water/Ultra-Deep Water Niger Delta area to generate shale-based pore pressure predictions from Sonic, Resistivity and Density logs where available. Finally these shale-based pore pressure predictions were compared with available wireline-conveyed pressure measurements (e.g MDT, RFT, etc) taken in associated sandstone reservoir intervals. Where reservoirs are thin and confined within shales the high correspondence between predicted shale pressures and measured reservoir pressures was proven. In areas where reservoirs are laterally extensive, often associated with thick packages of reservoir sand, there is evidence of either lateral transfer (higher reservoir pressures than predicted from associated shales) or lateral drainage (lower reservoir pressures than found in associated shales). The predominant observation in the Deep Water/Ultra-Deep Water Niger Delta area is for laterally drained reservoirs, especially in the stacked reservoir packages typical of parts of the Agbada Formation. Few wells penetrate the Akata Formation where confined reservoirs are expected to be more typical.

**Fracture Gradient Prediction**

A fracture gradient prediction can be determined from a published relationship (e.g. Daines, Eaton, Matthews and Kelly) where some rock attributes (e.g. Poisson’s Ratio) must be assumed. In addition almost all of the published algorithms are empirical observations based on analysis of Gulf of Mexico drilling locations and hence associated with Gulf of Mexico rock properties. An alternative approach, which can only be achieved where regional data are available, is based on examination of all the borehole fracture strength estimates from Leak Off Tests (LOTs). Each LOT is normally taken at a casing point, below which the fracture strength of the intact rock, plus the integrity of the casing shoe is determined. Each well is expected to offer only 3 or 4 such values but a dataset of over 100 wells provides an opportunity to examine both local and regional trends with sufficient data to add confidence to any subsequent interpretation.

The LOT data from Deep Water/Ultra-Deep Water Niger Delta area have provided the basis for delta-wide algorithms in the Eastern and Western Niger Delta areas which have a high level of internal consistency and can be applied with confidence in the future at new drilling sites.

**Defining the drilling window**

The drilling window in a well plan is defined by both pore pressure and fracture gradient predictions. Ideally an “expected” depth profile will be complemented by inclusion of “minimum” or “low” case and “maximum” or “high” case to capture the uncertainty of each. The range of profiles for a well
plan will result from detailed analysis of offset (local) well data applied to the expected rock column, but require understanding of the basin plumbing from regional pressure analysis. In addition to pore pressure prediction from shales (coupled to seismic velocity-based shale prediction at the well location) the approach taken in the study is to provide a “geological” reality check for the expected amount of overpressure from burial/stress related mechanisms. The study has explored where certain mechanisms are active as well as showing many comparisons between shale-based analysis and burial/stress-based estimates. The two combined add much more confidence to the prediction capability and hence to defining the drilling window in future well locations.

**Exploration Opportunities**

Tertiary deltas are well known worldwide for their high pressures – discovered during drilling operations, but also manifest in features such as mud volcanoes, fluid expulsion phenomena, velocity reversals on seismic data and growth faulting facilitated by wet (high porosity) clays buried to depth. High pressures have impact on many aspects of the petroleum system, including leading to high porosity sandstone reservoirs at depth, migration pathways and trapping of hydrocarbons, seal breach (Figure 2) and hydrodynamic effects in laterally connected and pressure-drained reservoirs.

Regional pressure analysis in the Deep Water/Ultra-Deep Water Niger Delta area has explored relationships between pore pressure and regional/local stress and fracture strength in order to predict where seal breach could lead to failed traps (and save valuable exploration dollars in avoiding drilling a dry hole). Further seal breach analysis has been investigated as one of a range of possible explanations for dry holes in the Deep Water Toe Thrust area. What is clear from the study is that there are packages of reservoir in which pressures are transferred, either locally to elevate pressures in the reservoir above local shale pressures, or regionally in connected aquifers in which reservoir pressures are lower than their associated (thick) shales. In many cases the stacked reservoirs show much lower than expected pressures. Global experience (by Ikon GeoPressure) of laterally drained reservoirs has offered analogues to assist in assessing the likely impact of such phenomena on hydrocarbon trapping, migration pathways and hydrocarbon type. One significant impact of pressure regressions associated with laterally draining reservoirs is the ability of the seal to support much longer hydrocarbon column heights. The natural seal capacity is enhanced by the requirement of the buoyancy pressure to exceed the additional overpressure – that is assuming adequate structural closure, of course!

Some examples of the main conclusions and exploration opportunities which have emerged from the study of the Deep Water/Ultra-Deep Water Niger Delta will be shown in the presentation.

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Figure 1. Types of data and algorithms (Eaton, etc) applied to shale-based pore pressure analysis, plus calibration data types recorded in associated reservoirs.

Figure 2. Schematic diagram of a continuous reservoir, whose overpressure has been determined from data from a well (e.g. far left oil discovery). The overpressure maps combined with regional knowledge can be used to predict seal breach in Prospect A (when fracture strength can also be estimated) as well as de-risking Prospect B.